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Conference Proceedings

Editors
Angeliki Tsorlini
Chrysoula Boutoura

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Thessaloniki: AUTH CartoGeoLab



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Preface

Historical maps are invaluable sources of knowledge about past societies, landscapes, and worldviews. Beyond their geographical content, they preserve evidence of historical processes, cultural developments, scientific advances, and artistic traditions. Exploring innovative ways to preserve, interpret, and make this information accessible for research and public engagement is a central objective of the International Cartographic Association (ICA) Commission on Cartographic Heritage into the Digital and the Map & Geoinformation Curators Group (MAGIC).

This volume brings together the papers presented at the 20th Conference on Digital Approaches to Cartographic Heritage (ICA DACH). The contributions demonstrate the richness and diversity of hi-storical map collections and highlight their potential for research across a wide range of scientific and artistic disciplines. They also illustrate how digital technologies create new opportunities for studying, interpreting, and disseminating cartographic heritage.

This year's conference features 43 papers from 16 countries, representing 41 institutions, including universities, libraries, archives, museums, research institutes, and organisations from the public and private geospatial sectors. Organised into eight working sessions, the programme addresses key topics within the remits of the ICA Commission and MAGIC, including research and development in cartographic heritage, interdisciplinary cooperation, public engagement, map collection development strategies, metadata and data-exchange standards, preservation and access, innovative visualisation and virtual exhibitions, and the intersections of cartographic heritage with the digital humanities.

The diversity of contributions reflects the evolving nature of the field, bringing together researchers, curators, librarians, archivists, and other professionals to exchange knowledge and explore new approaches to the study and preservation of historical cartographic materials.

We hope this volume will provide valuable insights and inspiration for all those working in cartographic heritage and map librarianship, encouraging further collaboration and research in this dynamic field.

Mátyás Gede
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Asimamaw Nigusie Asitatikie*[1,2,3], Remus Cretan[2], Roberto Ranzi[1], Stefano Barontini[1], Giovanna Grossi[1]

Long-Term Land-Use and Land-Cover Transformations over the Last Two Centuries in Eastern Italian Alps: The Case of the Piave River Basin

Keywords: Historical Cartography, Land Use/Land Cover Transformation, Second Military Survey, Piave Basin

Summary: This study aims to assess land use and land cover transformations over the last two centuries by reconstructing the evolution of the landscape in the Piave River Basin from the beginning of the Little Ice Age recession to present time.
Georeferenced ancient military survey maps of the Habsburg Empire dating back to the 19th century are currently available online, synchronized with modern base maps: https://maps.arcanum.com/en/, but so far, they have not been systematically investigated to detect environmental landscape transformations. This is the aim of this study, presenting comprehensive LULC detection spanning nearly two hundred years, connecting the Habsburg era (namely, 1818-1829) and the CORINE 2018 land cover dataset in the Piave River basin.
The re-georeferenced and manually digitized Cartographic Maps (1818-1829) of the Habsburg Empire -Second Military Survey for the Piave River Basin (Eastern Italian Alps), covering an area of 4154.02 km^2, were prepared and compared with the present Corine-based (2018) land use and land cover classifications. Nine macro classes were identified and tracked, including Forest (broad-leaved trees, conifers, mixed woods), Arable Land, Pastures/Natural Grassland, Water Bodies, Glaciers, Bare Rocks, Garden/Leisure Facilities, Road/Rail networks, and Urban/Built-up Areas.
The analysis revealed a notable reduction in Bare Rocks by 373.83 km^2 (-53.27%) and a decline in Arable Land by 41.59 km^2 (-13.79%) from the Habsburg era to 2018. Glacier coverage also decreased by 37.03 km^2.
Conversely, Forests, which were the dominant land cover class covering an area of 2424.60 km^2 (58.35% of the basin) during the Habsburg era, significantly increased by 297.57 km^2 (+12.27%), as is the case for Pastures/Natural Grassland (94.15 km^2, +14.5%) and Urban/Built-up Areas (69.18 km^2, +667.85%).
These findings provide quantified historical references. They will add significant value to future sustainable land and environmental management, biodiversity and ecosystem restoration, water resource planning, and the development and conservation of tangible cultural heritage in the Alps and other mountainous catchments.

Introduction

Since the beginning of the Little Ice Age recession in the early 19th Century, Alpine mountain ranges have undergone profound land-use and land-cover (LULC) transformations, driven by an interplay between human societies and the natural environment (Zimmermann et al., 2010). The historical catchment systems have altered, and the traditional landscape characters are reshaped as a result of long-term environmental processes, socio-economic changes, and climatic variability (Carrer et al., 2020).
Over the past two centuries, the abandonment of mountain agriculture and a subsequent intensification of productive lowland areas, demographic shifts, the rural mountain depopulation, and the rapid urbanization of valley floors caused significant changes in landscape management practices, modifying the Alpine ecosystem functioning and composition (MacDonald et al., 2000; Tasser et al., 2007). To examine such a landscape evolution, the Piave River Basin was selected as a representative case study, given its well-documented ancient military survey maps since the 19th Century

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and adequate modern high-resolution satellite data, which are available through the Corine Land Cover Project (Cover, 2018). This basin, situated in the Eastern Italian Alpine Region, features a diverse range of topographic gradients and is characterized by varied lithology and land cover types, including extensive evergreen forests mixed with natural grasslands, high-altitude bare rocks and glaciers, valley floor arable lands, and increasing urban areas (Di Grazia et al., 2021).

Before the launch of modern high-resolution remote sensing datasets, ancient cartographic maps provide valuable landscape records. Among these historical resources, the Habsburg Empire -Second Military Survey (1806-1869) offers detailed illustrations of infrastructure, settlements and roads, land use features with specified colors at the scale 1:28,800 (Timár et al., 2006), covering most of Central Europe, including northern Italy, where this study was conducted in the period 1818-1829. These maps were later georeferenced and synchronized with modern base maps and are publicly accessible at https://maps.arcanum.com/en/. They depict the contemporary land-use features, which enable historical land-use trajectory analysis (Kovács, 2009; Ostafin et al., 2021; Ranzi et al., 2021).

Despite their invaluable potential for examining long-term landscape evolution, the Habsburg Second Military Survey maps have received little attention in geographical and environmental research, particularly in the Italian Alps. Numerous previous works have largely concentrated on the Carpathian and the Austrian portions of the Alps (Kaim et al., 2016; Kaim et al., 2018; Lieskovský et al., 2018; Munteanu et al., 2016; Ostafin et al., 2021), while comparable landscape reconstructions within the Italian Alpine regions are confined to non-basin scale and short time windows, such as the studies conducted by M Balistrocchi et al. (2021), Ranzi et al. (2022). Another study conducted by Roccati et al. (2018) reconstructed the long-term LULC transformations in small catchments of the Liguria region, leaving the Piave River Basin specifically still systematically underrepresented. Therefore, a significant basin-scale study focusing on the quantitative analysis and reconstruction of land use and land cover change over the past two centuries is missing, and this work addresses this gap by presenting comprehensive LULC detection results for the Piave Basin spanning nearly two hundred years, connecting the Habsburg era and the CORINE 2018 land cover dataset. The study incorporated re-georeferencing of the pre-existing georeferenced Habsburg Second Military Survey cartographic maps to the specific Piave basin scale, manual and systematic digitization and comparison with high-resolution remote sensing-derived CORINE 1990 and 2018 products, enabling detection of changes across the three distinct temporal snapshots: Habsburg 1818-1829, CORINE 1990 and CORINE 2018. Nine major land covers were examined, including Forest (broad-leaved trees, conifers, mixed woods), Arable Land, Pastures/Natural Grassland, Water Bodies, Glaciers, Bare Rocks, Garden/Leisure Facilities, Road/Rail networks, and Urban/Built-up Areas.

The main aim of this work includes quantifying the magnitude and characterizing the direction and spatial patterns of LULC transformation over the long-time frame, examining the possible drivers and accompanying processes responsible for detected changes, including political, social, economic, and agricultural policies and transitions, and climate change, as well as discussing the significant implications of these land cover shifts for ecosystem and biodiversity services, hydrological cycle processes, and cultural environment heritage across the Piave River Basin.

Study Area

The Piave River basin is located in the Veneto Region (North-eastern Italy), with its largest area lying in the Eastern Italian Alpine regions (Figure 1). The basin originates in the Sexten Dolomites,

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near Tre Cime Nature Park and Fanes-Senes-Braies Nature Park and then extends southwest towards the Paneveggio-Pale di San Martino National Park and southeast towards the Dolomiti Bellunesi National Park. Geographically, it spans roughly from 11^0 30' E to 12^0 43' E in longitude, and from 45^0 52' N to 46^0 41' N in latitude, with elevations ranging from 180 m.a.s.l. in lower fields to 3,309 m.a.s.l at higher altitudes and covers a total area of approximately 4154.02 km^2 upstream of the village named Sequsino.

The basin features a pronounced elevation gradient that leads to marked contrast in land use, vegetation, and climate across the piedmont, valley floors, pre-alpine, and high-alpine zones. Mesozoic carbonates and crystalline rocks dominate the upper parts of the basin, where pre-glacial and glacial features indicate Quaternary glaciation (Carton et al., 2009).

Historically, human occupation in the Piave basin dates back to the Bronze Age, with well-preserved evidence of a Roman settlement and transportation networks on the valley floor (Comiti et al., 2011; Roncaglia, 2018). Under the Habsburg Empire in the 19th century, the basin adopted a predominantly pastoral and agricultural economy, with widespread mountain grazing (‘malghe’) and croplands across the valley plain fields (Gabellieri & Sarzotti, 2024). Additionally, harvesting Timber from the basin’s extensive conifer forest constituted a major economic activity, contributing resources to the Venetian Arsenal and later supplying local industrial uses (Gabellieri & Sarzotti, 2024). In the First World War, the basin underwent significant economic and demographic disruption, serving as the principal border of Italian confrontation against Austro-Hungarian forces between 1917 and 1918 (Raab, 2004).

However, after the war, the catchment experienced accelerated urbanization and abandonment of marginal mountainous agropastoral areas, followed by intensification of agriculture on lowland and valley floors and forest expansion in the abandoned mountainous regions (Comiti et al., 2011; Garbarino et al., 2020; MacDonald et al., 2000).

Today, the basin encompasses major urban centers, including Feltre, Pieve di Cadore, and Belluno. It also preserves a notable UNESCO World Natural Heritage site, "**The Dolomites**", such as Dolomiti Bellunesi, Marmolada, Valle di San Lucano, and Vette Feltrine (https://whc.unesco.org/en/list/1237), with several other natural attractions.

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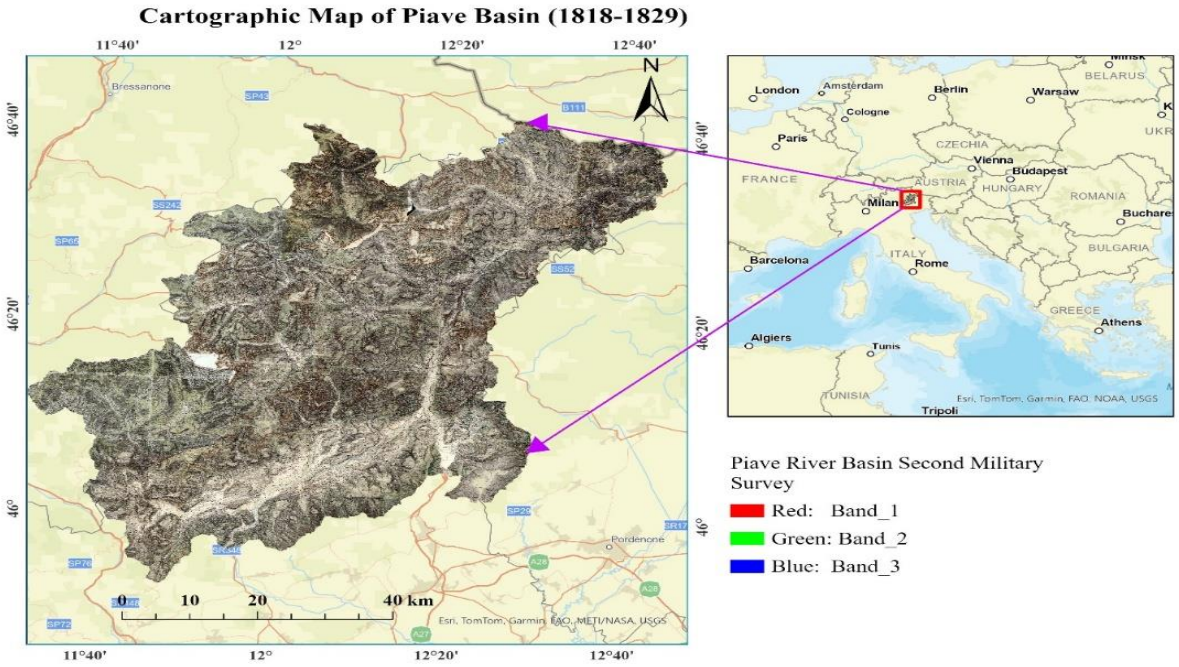

Figure 1. Location of the Piave Basin, situated between the Fanes-Senes-Braies and Dolomiti Bellunesi Nature Parks, and encompassing **"The Dolomites"** in the Veneto Region (North- Eastern Italy). Source: Arcanum Maps (https://maps.arcanum.com/en/)

Data Sources and Methodology

Habsburg-Second Military Survey Cartographical Map

The ancient Habsburg-Second Military Cartographic Map (also known as the Franciscan Map), surveyed from 1818 to 1829 in Northern Italy and currently accessible at https://maps.arcanum.com/en/, was used as a primary data source. This historical map was initially produced by the military administrations of the Habsburg Empire by generating topographic and land-use records across the state territories at a 1:28,800 scale, later georeferenced and rectified, making it a remarkably spatially consistent and detailed historical cartographic fact sheet in the history of Europe. It offers a surprisingly good rectification result with a maximum error of 200 meters and can be an invaluable source to detect the long-term built and natural landscape changes in Central Europe (Timár et al., 2010; Timár et al., 2006). For the Italian Alpine regions, the map was surveyed from 1818 to 1829, producing a series of survey sheets covering the Lombardy and Veneto territories in significant spatial and thematic detail (Timár et al., 2006). This cartographical survey illustrates diverse land-use features essential to this manuscript analysis, and its thematic content is interpreted using well-established Habsburg cartographic survey legend conventions (Konkoly-Gyuró et al., 2017; Pap et al., 2015), integrating cross-referencing with current ground control points and modern geographical base maps. For this study, the cartographic map was vectorized according to the CORINE land cover classification, as depicted in Table 1.

Table 1: Sample images of the Habsburg-Second Military Survey with Corine LULC classification

No	Second Military Survey	Corine Land Cover	Reclassified LULC
1		Non-irrigated arable land	Arable Land

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		Complex cultivation patterns Land principally occupied by agriculture	
2		Continuous urban fabric Discontinuous urban fabric Industrial or commercial units	Urban and Built-Up Areas
3		Road and rail networks Airports Mineral extraction sites Dump sites Construction sites	Road and rail networks
4		Natural grasslands Moors and Heathland Inland marshes	Pastures and Natural grasslands
5		Broad-leaved forest Coniferous forest Mixed forest Transitional woodland-shrub	Forest
6		Beaches, dunes, sands Bare rocks	Bare rocks

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7		Permanent ice and Perpetual snow	Glaciers
8		Water courses (Rivers) Water bodies (Lakes, Reservoirs)	Water Body

Georeferencing

Even though the historical digital cartographic data used in this study was sourced from a pre-georeferenced map, re-georeferencing it at the basin scale enhances its accuracy and alignment in representing geographical and spatial features on the actual ground surface. Georeferencing historical maps involves using topographic features, such as roads, churches, urban centres, lakes, and other natural and man-made objects that should be present in the mapping period and today. For this study, georeferencing was carried out using coordinates of five lake corners, dispersed across various locations in the basin and dating from the Habsburg era to the present, to minimize errors and maximize accuracy in a GIS environment (QGIS 3.44.11). In each selected point, the actual measured ground control coordinates were paired with the corresponding pixel coordinates on the pre-georeferenced historical maps in the Georeferencer plugin, using a transformation type of first-order polynomial, which avoids overfitting when small ground control points are applied, since the pre-georeferenced historical map at the basin scale is nearly planar. Fortunately, the Piave basin is endowed with various small ponds and small to medium-sized lakes fixed over more than two centuries, and reference lakes were taken from those distributed in the western, southwestern, southeastern, northern, and northeastern parts, considering the overall spatial extent of the basin, including the high-elevation northern and western portions.

Manual digitization and classification

Manual digitization of the Second Military Survey was performed to prepare contemporary LULC data by delineating each land-use area as closed polygons from basin-scale re-georeferenced cartographic map tiles and attributing them to predefined macro classes. Nine major land cover classes (Table 1) were established, compatible with the reclassified primary CORINE land cover classification system to enable consistent trans-temporal comparisons. The vectorized map was generated for the entire drainage area, using the basin boundary as the spatial mask.

CORINE land cover dataset

The CORINE Land Cover (CLC) Program was initiated by the European Commission in 1985 to support environmental monitoring across Europe, producing land cover data every six years, beginning in 1990. The program consists of 44 LULC classification systems, ranging from broad categories to detailed subclasses, and these land cover classifications constitute the most consistent and

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comprehensive dataset used for environmental change detection analysis at the regional and basin scales (Feranec et al., 2007; Feranec et al., 2010; Viola et al., 2026).
This study reclassified 21 sub-categorical land cover classes obtained from the CLC into nine macro classes for the 2018 reference datasets, as illustrated in Table 1, columns 3 and 4. The 1990 Corine Land Cover data were also selected and examined, serving as an intermediate cross-temporal snap-shot that enabled change detection analysis across the two long-term periods and one short-term period: Historical era (1818-1829), intermediate 1990, and current 2018.

Long-term change detection analysis and transition matrix

The area of each major class was calculated for each selected period to analyze long-term LULC change. Relative area changes were computed between successive time intervals (1829-1990 and 1990-2018) and over the entire period (1829-2018) using the intersection Geoprocessing Analysis tool in ArcGIS Pro, which produces a transition matrix for each interval. The resulting tabulated statistics were analyzed to detect net area changes, dominant transitions, and the consistency of each land cover class over the entire study period, and the results were illustrated in diagrams.

Results

Georeferencing

Georeferencing inaccuracies directly affect the spatial representation of the identified LULC class on the ground, resulting in potential errors in long-term transition analysis. In this study, eleven well-identified lake corner coordinate points, including corner coordinate points from Lake Santa Croce in the southeastern part, Lake Misurina in the north, Lake Cavia in the west, Lake Olbe in the northeastern part, and Lake Bus in the southwestern part, were utilized as ground control points for re-georeferencing the Second Military Survey at the basin scale (see Table 2).
Since the pre-georeferenced historical maps were not tailored to the specific extent of the Piave basin, the Habsburg sheets were re-georeferenced at the basin scale using the eleven actual ground control coordinate points described above, thereby improving the spatial and geographical fidelity of the subsequently vectorized LULC boundaries.

Table 2: Actual ground control points on different lake corners relative to the pre-georeferenced Habsburg Second Military Survey across the basin

No	Lake Name	Coordinates on the pre-georeferenced historical map		Coordinates on the actual ground	
		X	Y	X	Y
1	Lake Santa Croce	293332.75	5111120.86	293723.55	5112109.91
2	Lake Santa Croce	294101.00	5107417.00	294099.94	5107491.88
3	Lake Santa Croce	294401.20	5107403.00	294471.62	5107496.73
4	Lake Misurina	289769.20	516287.30	289817.70	5162398.21
5	Lake Misurina	289535.00	5162081.00	289499.86	5162214.80
6	Lake Cavia	255175.60	5139012.70	255044.14	5139119.85
7	Lake Cavia	255330.50	5139000.20	255265.42	5138950.13

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8	Lake Olbe	323542.60	5162623.60	323308.30	5162931.95
9	Lake Olbe	323215.50	5162602.70	323152.98	5162905.18
10	Lake Bus	237508.10	5120707.40	237972.30	5120038.20
11	Lake Bus	237273.40	5120729.30	237752.27	5120087.34

The Habsburg (1818-1829) LULC distribution

The spatial and numerical narrative of each primary LULC class along the three snapshot periods in the Piave basin is presented in Table 3 and Figures 2-4. These figures and numerical values illustrated long-term progressive northeasterly and central afforestation/reforestation, bar rocks and glacier colonization, against urban expansion and agricultural contraction in the southern valley floors, as well as pastoral expansion dispersed across the entire basin. During the Habsburg period, forests were the dominant land cover class, covering a total area of 2424.60 km^2 (58.35%). These reflected widespread subalpine and mountainous coniferous, mild-slope mixed forests, and valley floor woodlands, forming a continuous evergreen landscape across the northeastern and central portions of the basin (Figure 2). Bare Rocks/Sands were the second LULC class, constituting 701.78 km^2 (16.89%) of area, indicating the prominence of high- elevation rocky and scree terrain, glacially scoured ridgeline concentrated mainly on the northwestern parts, with extensive gravel and sand bars along the braided bed and reaches of the main and its tributaries of the Piave River.
Pastures and Natural Grasslands were the third class, occupying an area of 648.75 km^2 (15.61%), reflecting the extensive alpine and subalpine managed summer pastoral('malghe') traditions and grassland systems, scattered between the rock and forest transitions in the southwestern part of the basin during the 19th century. Arable land covers, 301.60 km^2 (7.25%), were distributed mainly in the southern piedmonts and valley bottoms, where alluvial fertile soils supported intercropping of viticulture and cereal crop cultivation, and on mountain slopes. Glaciers took up 37.53 km^2 (0.90%), perched and isolated among the high-elevation peaks of the Dolomites. Water bodies were 24.72 km^2 (0.59%), and Urban/Built-Up Areas and associated road/railway networks accounted for 10.36 km^2 (0.25%) and 5.57 km^2 (0.13%), respectively, reflecting pre-industrial settlements in the Piave Basin during the Habsburg era. Garden and leisure facilities did not exist, which were not common activities during that period.

Table 3: Major LULC classes of the Piave River Basin over the three time periods

	Area (km^2)		
LULC Class	1818-1829	1990	2018
Urban and Built-Up Areas	10.36	68.95	79.54
Road and rail networks	5.57	3.04	2.48
Arable Land	301.60	325.08	260.01
Pastures and Natural Grassland	648.75	583.67	742.90
Glaciers and Perpetual Snow	37.53	1.87	0.50
Forest	2424.60	2817.15	2722.16
Bare rocks	701.78	339.68	327.95
Water bodies	24.72	14.93	15.12
Garden and leisure facilities	0.00	0.52	4.25

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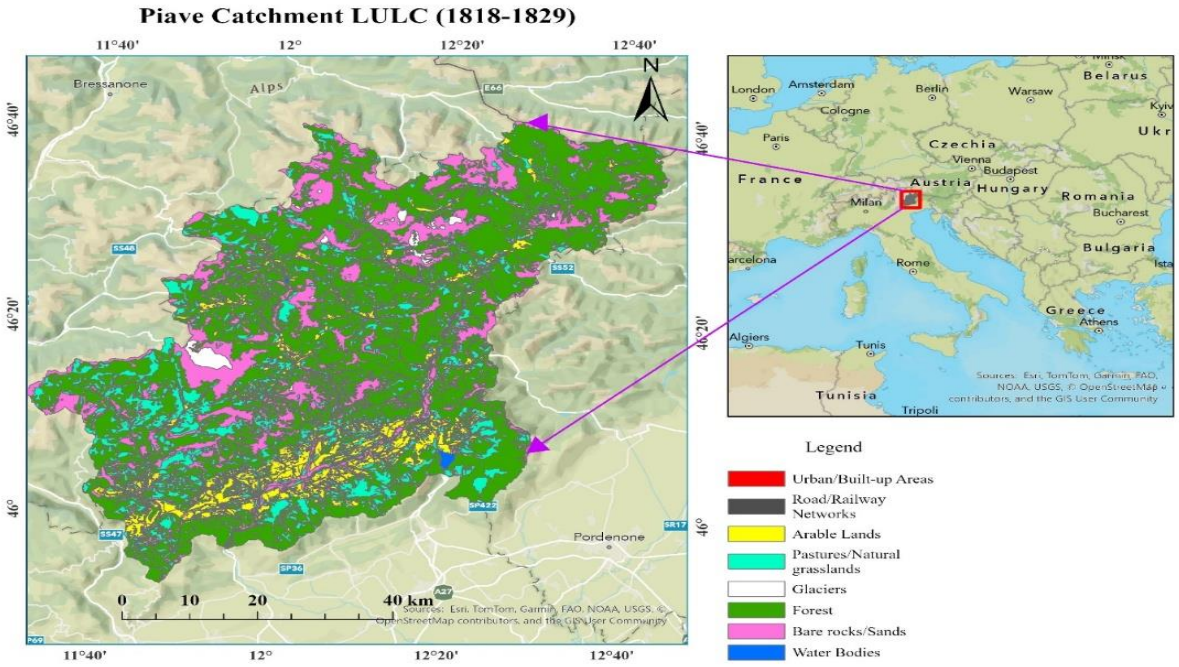

Figure 2. Spatial extent of the primary LULC classes in the Piave Basin during the Habsburg period (1818-1829), prepared from digitizing the Habsburg Second Military Survey

The modern reference CORINE Land Cover

In the 1990 and 2018 CORINE Land Cover classifications, most classes showed an overall similar pattern; forests constituted the largest portions of the basin, occupying 2817.15 km^2 (67.8%) and 2722.16 km^2 (65.5%), respectively, persisting from their former classes and colonizing pastures, bare rocks, and arable lands (see Table 3, Figures 3 and 4). Pastures and natural grassland covered 583.67 km^2 (14.05%) in 1990 and 742.90 km^2 (17.88%) in 2018, followed by bare rocks, which accounted for 339.68 km^2 (8.17%) in 1990 and 327.95 km^2 (7.89%) in 2018.
Accounting for 325.08 km^2 (7.8%) in 1990 and 260.01 km^2 (6.25%) in 2018, arable lands are more concentrated only in the southern valley floors and piedmonts. Urban and built-up areas, rising sharply to 68.95 km^2 (1.66%) and 79.54 km^2 (1.91%) in 1990 and 2018, respectively, form visibly small, distinct clusters on the southern valley-floor corridors and roads. Glaciers covered 1.87 km^2 in 1990 but only 0.5 km^2 in 2018, reflecting their complete retreat from the basin compared to the Habsburg era. New gardens and leisure facilities appear in these reference times, though it was very small in 1990 (0.52 km^2) to be prominent for this basin, it slightly rose to 4.25 km^2 in 2018.

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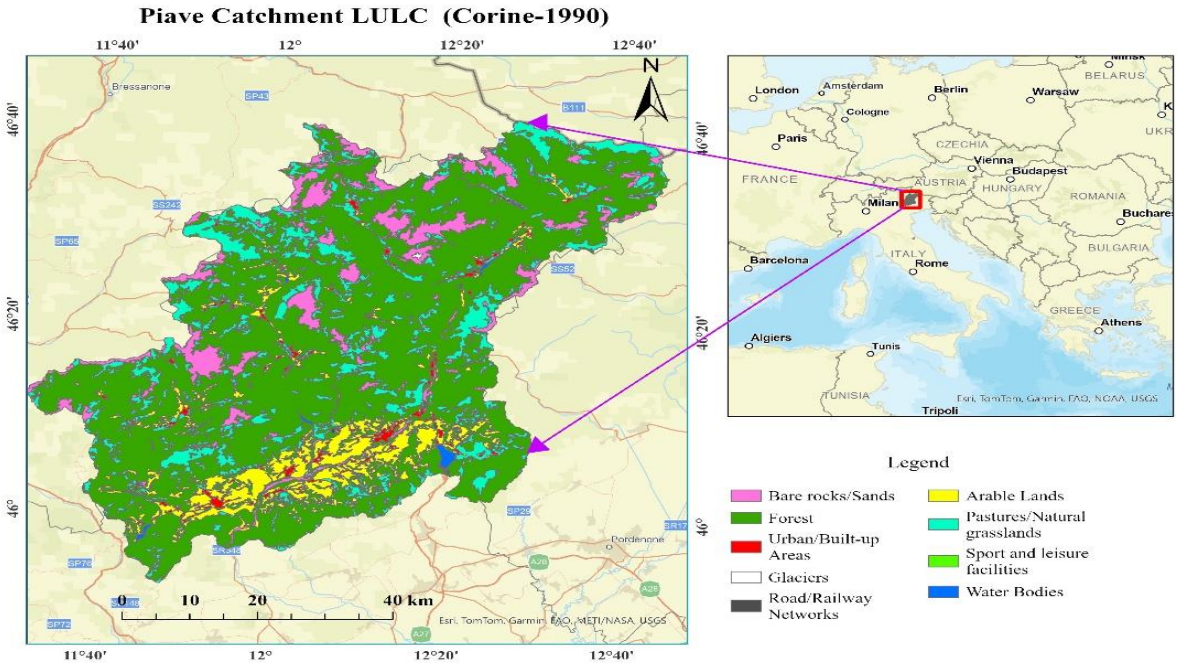

Figure 3. LULC classes in the Piave Basin in 1990, derived and reclassified from the CORINE Land Cover

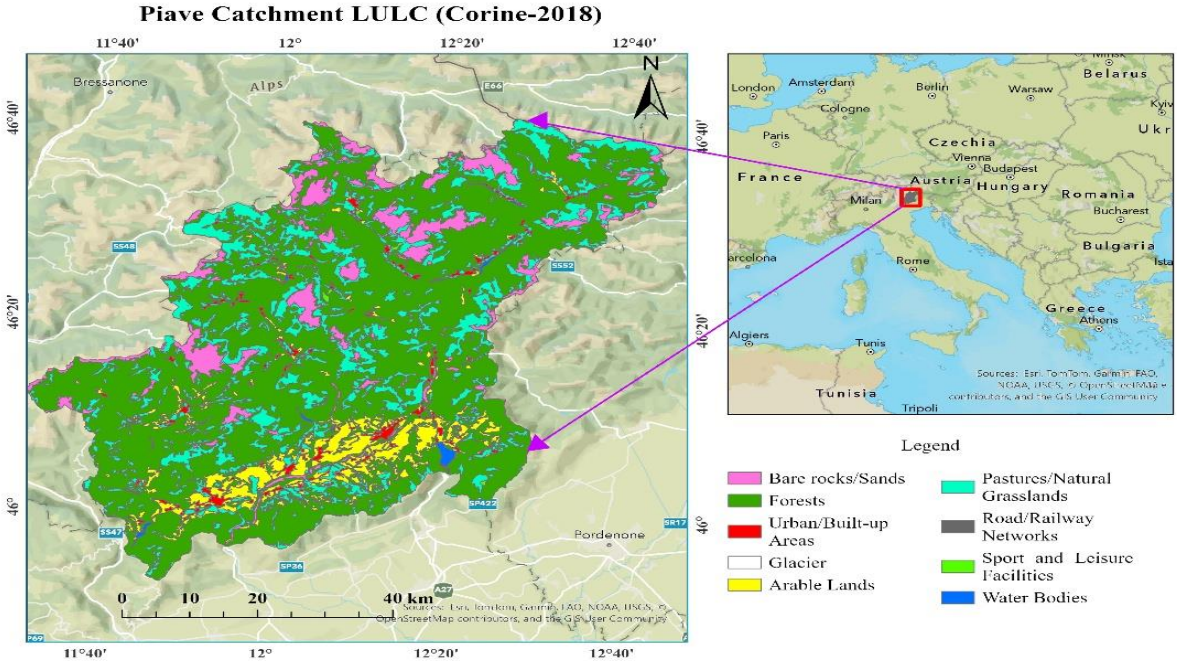

Figure 4. Modern reference period (2018) major LULC classes in the Piave Basin, generated from the CORINE Land Cover

Temporal LULC Changes across the study period (1829–2018)

Table 4 summarizes the area changes of each LULC between the progressive and the entire study period. Bare Rocks/Sands LULC class showed a significant transformation, declining by 373.83 km^2 (-53.27%) over the long-term period from the Habsburg era to 2018. This extraordinary reduction is probably due to the successive expansions of land vegetation cover on deglaciated terrain

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and the advance of alluvial and riparian vegetation onto gravel bars, following the recession of the Little Ice Age in the 19th Century, as the climate began to warm (Comiti et al., 2007).

Forest cover showed notable expansion, with a net area gain of 297.57 km^2 (+12.27%) over the entire study period, supported by forest expansion patterns in the European mountains following the abandonment of traditional, marginalized agropastoral practices and rural depopulation during the 20th century (MacDonald et al., 2000). Even though Pastures and Natural Grasslands exhibited a consistent encroachment of forests on abandoned mountainous pastures in the 20th century, declining by 65.09 km^2 (-10.03%) between 1829 and 1990, their net gain area rose by 94.15 km^2 (+14.5%) for the full study period, against these encroachments, representing genuine grassland management recovery linked to the instruments of European Union environmental and agricultural policy (Batary et al., 2015; Pazúr et al., 2024).

Arable lands yield a net area loss of 41.59 km^2 (-13.79%) across the entire period, because of rural and marginal mountainous agricultural abandonments, and concentrate only on the valley-floors and piedmonts. Urban and built-up areas increased significantly, with a net area gain of +69.18 km^2 (+667.85%), reflecting the expansion of urbanization in the Belluno valley and Venetian Piedmont following rapid economic growth and improved living standards (Piccinato, 1993). Glacier coverage decreased significantly with a net loss of 37.03 km^2 (-98.67%), signaling its irreversible disappearance from the Piave drainage basin, and indicating the Alpine cryosphere's climate warming at the end of the 20th and into the 21st centuries (Securo et al., 2025; Sommer et al., 2020).

Table 4: Area changes of each LULC between progressive time periods and the entire study period (1829-2018)

LULC Class	1829 -1990 change [Km^2 (%)]	1990-2018 change [Km^2 (%)]	Net Change (1829-2018) [Km^2 (%)]
Urban and Built-Up Areas	+58.60 (565.69%)	+10.58 (+15.34%)	+69.18 (+667.85%)
Road and rail networks	-2.53 (-45.38%)	-0.57 (-18.61%)	-3.09 (-55.54%)
Arable Land	+23.48 (+7.78%)	-65.07 (-20.02%)	-41.59 (-13.79%)
Pastures and Natural Grassland	-65.09 (-10.03%)	+159.23 (+27.27%)	+94.15 (+14.5%)
Glaciers	-35.66 (-95.01%)	-1.37 (-73.27%)	-37.03 (-98.67%)
Forest	+392.56 (16.19%)	-94.99 (-3.37%)	+297.57 (+12.27%)
Bare rocks	-362.10(-51.59%)	-11.73 (-3.45%)	-373.83 (-53.27%)
Water bodies	-9.78 (-39.57%)	+0.18 (+1.21%)	-9.60 (-38.84%)
Garden and leisure facilities	+0.52 (+100%)	+3.73 (+710%)	+4.25 (100%)

Dominant LULC Transitions across the study period

Three tabulated transition matrices (Tables 5-6) and their corresponding schematic diagrams (Figures 5-7) were developed to represent the dominant directional net area exchanges in each LULC class during the successive and overall study periods.

From 1829 to 1990, a notable conversion of Pastures/Natural Grasslands and Bare Rocks/Sands to Forests occurred, increasing by 383.3 km^2 and by 379.7 km^2, respectively (see Table 5 and Figure 5), which supports widespread afforestation of abandoned mountain grazing lands and formerly

bare terrains. On the reverse, a significant flow was observed from Forests to Pastures/Natural Grasslands, converted by 318.0 km^2, and a substantial transition to Arable Lands by 78.7 km^2, reflecting locally dynamic forest boundaries despite the overall inhabited class expansion.
Forests ranked first in persistence, preserving an area of 1955.2 km^2, followed by Bare Rocks/Sands and Pastures/Natural Grasslands, which sustained their former areas of 234.0 km^2 and 159.0 km^2, respectively.

Table 5: LULC Transition matrix between 1829 and 1990

LULC Class		**LULC 1990 (km^2)**									
		1	2	3	4	5	6	7	8	9	**Total**
LULC 1829	Urban Areas (1)	3.5	0.0	3.2	1.7	-	1.9	0.1	0.0	-	**10.4**
	Road (2)	1.3	0.1	1.5	0.6		1.8	0.2	0.0	-	**5.6**
	Arable Land (3)	36.0	0.6	152.8	29.2	-	77.2	2.5	3.4	0.0	**301.6**
	Grasslands (4)	12.6	1.3	77.7	159.0	-	383.3	12.8	1.8	0.2	**648.8**
	Glaciers (5)	-	-	-	1.6	0.6	7.6	27.8	-	-	**37.5**
	Forest (6)	11.1	0.5	78.7	318.0	0.0	1955.2	59.0	1.7	0.3	**2424.6**
	Bare rocks (7)	3.5	0.5	8.9	72.1	1.2	379.7	234.0	1.8	0.0	**701.8**
	Water (8)	1.0	0.1	2.2	1.5		10.2	3.7	6.1	0.0	**24.7**
	Total	**69.0**	**3.0**	**325.0**	**583.6**	**1.8**	**2816.9**	**340.0**	**14.9**	**0.5**	**4154.9**

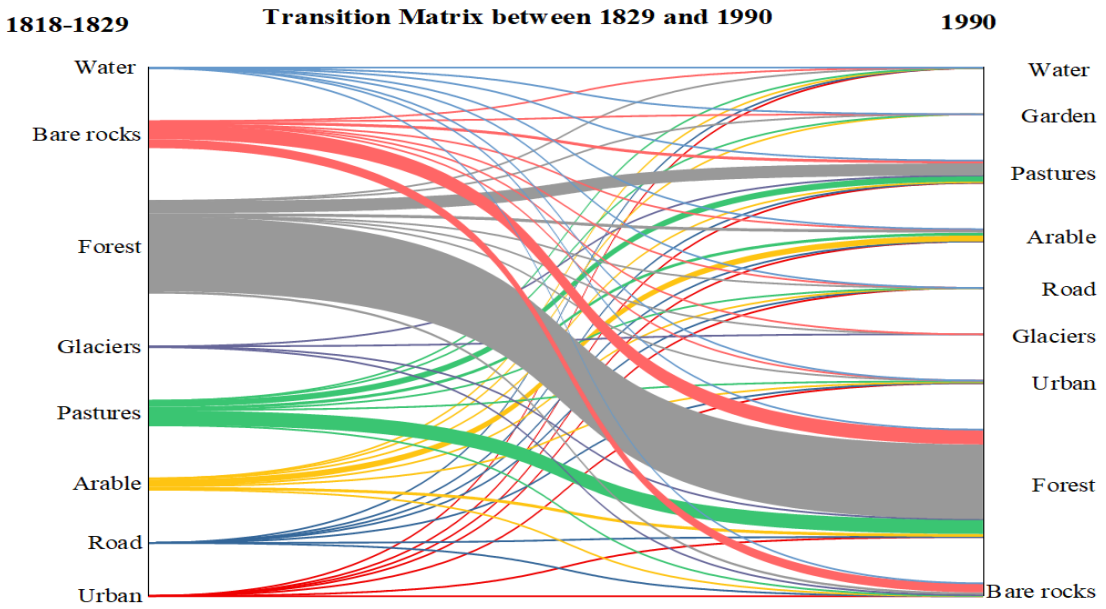

Figure 5. Schematic diagram of LULC transition matrix between 1829 and 1990, corresponding to Table 5.

Between 1990 and 2018, the most prominent class flows were from Forest to Pastures/Natural Grasslands by 195.2 km^2, followed by less than half of the reverse transition from Pastures/Natural Grasslands to Forest, which gained 80.9 km^2 (see Table 6 and Figure 6), reflecting grassland expansions in this period, as recorded in Table 4. Arable Lands contributed a net area of 51.6 km^2 to

Pastures/Natural Grasslands, while Forests received 21.1 km^2 and 20.9 km^2 from Bare Rocks/Sands and Arable Lands, respectively. High persistence remained in the Forest class (2597.7 km^2), Grasslands (492.8 km^2), and Bare Rocks (314.6 km^2).

Table 6: LULC Transition matrix between 1990 and 2018

		LULC 2018 [km^2]									
	LULC Class	1	2	3	4	5	6	7	8	9	**Total**
LULC 1990	Bare rocks (1)	314.6	21.1	0.2			1.1	2.7			**339.7**
	Forest (2)	10.4	2597.7	2.4		0.3	8.0	195.2	2.9	0.3	**2817.2**
	Urban Areas (3)	0.0	0.7	66.3		0.0	1.3	0.7	0.0		**69.0**
	Glaciers (4)	1.4			0.5						**1.9**
	Road (5)	0.2	0.8	0.0		2.1		0.0		0.0	**3.0**
	Arable Land (6)	0.7	20.9	6.0			245.7	51.6	0.2	0.0	**325.1**
	Grassland (7)	0.5	80.9	4.7		0.1	3.9	492.8	0.6	0.1	**583.7**
	Garden (8)								0.5		**0.5**
	Water (9)	0.2	0.1	0.0			0.0	0.0		14.7	**14.9**
	Total	**328.0**	**2722.2**	**79.5**	**0.5**	**2.5**	**260.0**	**742.9**	**4.3**	**15.1**	**4154.9**

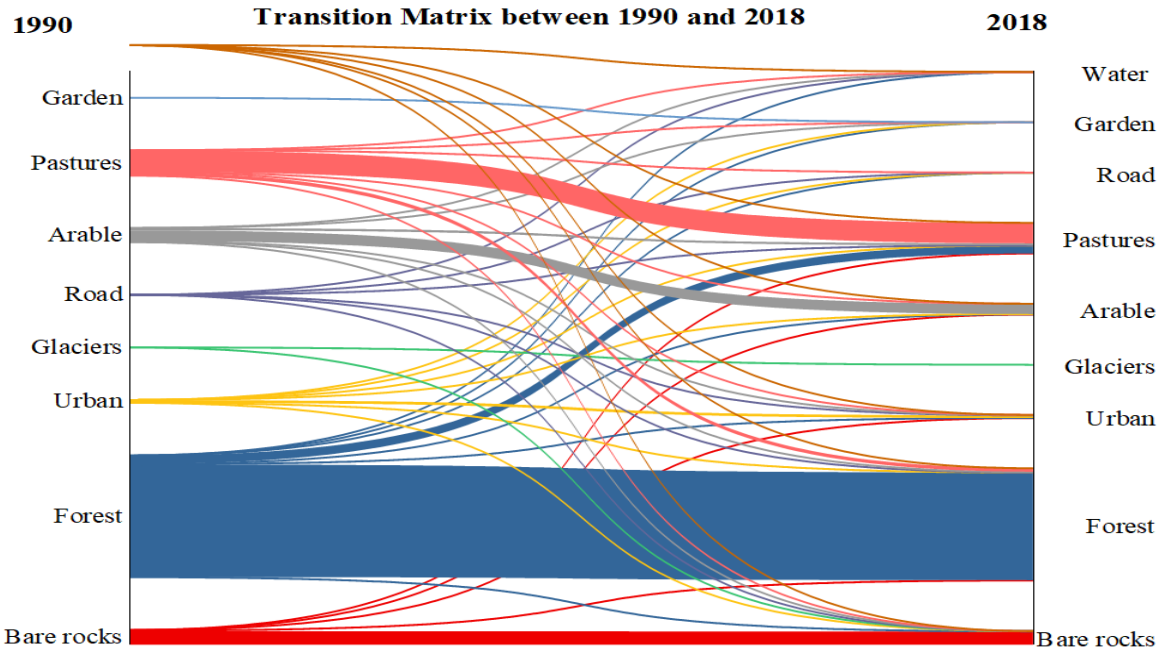

Figure 6. Schematic diagram of LULC transition matrix between 1990 and 2018, corresponding to Table 6.

Across the two-century study period, the dominant directional LULC exchanges were the conversion of Forest to Pastures/Natural Grasslands (395.5 km^2) and the nearly balanced reverse flow from Pastures/Natural Grasslands to Forests (390.1 km^2), as tabulated in Table 7 and depicted in Figure 7, which underscores the net gain results for both classes as shown in Table 4. During this long-term trajectory, Bare Rocks contributed the largest area to Forests, with a net conversion of 335.0 km^2, and to Pastures/Natural Grasslands (123.6 km^2, net gain from Bare Rocks), supporting the growth of vegetation on formerly rocky surfaces (Gennaro et al., 2023; Ramskogler et al., 2023).

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Forest also gained a net area of 79.4 km^2 from arable lands, while it contributed to Arable Lands (59.2 km^2) and to bare rocks (53.9 km^2). On the other hand, the Arable Lands received 65.2 km^2 from Pastures/Natural Grasslands but experienced a net loss of 52.4 km^2 to Pastures/Natural Grasslands and 41.6 km^2 to Urban and Built-Up Areas. Additionally, Glaciers played an important role in Bare Rock areas by predominantly feeding a net area of 28.4 km^2. These Glacier areas were then colonized by high-elevation vegetation (Eichel, 2018), thereby characterizing the long-term land-use transformation of the basin. Furthermore, a net area of 14.5 km^2 from Pastures/Natural Grasslands and 13.4 km^2 from Forests classes were converted to Urban and Built-Up Areas. A comparatively small but significant LULC conversion occurred, such as from Pastures/Natural Grasslands to Bare Rocks (11.7 km^2), along with other minor individual but collectively non-negligible exchanges.

Table 7: LULC Transition matrix across the full study period (1829- 2018)

		LULC 2018									
	LULC Class	1	2	3	4	5	6	7	8	9	**Total**
LULC 1829	Urban Areas (1)	3.8	0.0	2.4	2.2	-	1.9	0.0	0.0	0.0	**10.4**
	Road (2)	1.4	0.1	1.4	0.6	-	1.9	0.1	0.0	-	**5.6**
	Arable Land (3)	41.6	0.6	122.5	52.4	-	79.4	1.5	3.5	0.2	**301.6**
	Grassland (4)	14.5	1.4	65.2	162.6	-	390.1	11.7	1.9	1.4	**648.8**
	Glaciers (5)	-	-	-	4.5	-	4.6	28.4	-	-	**37.5**
	Forest (6)	13.4	0.2	59.2	395.5	-	1897.9	53.9	1.8	2.6	**2424.6**
	Bare rocks (7)	3.7	0.2	7.7	123.6	0.5	335.0	229.2	1.8	0.1	**701.8**
	Water bodies (8)	1.1	0.0	1.6	1.5	-	11.4	3.0	6.1	0.0	**24.7**
	Total	**79.5**	**2.5**	**260.0**	**742.9**	**0.5**	**2722.2**	**328.0**	**15.1**	**4.3**	**4154.9**

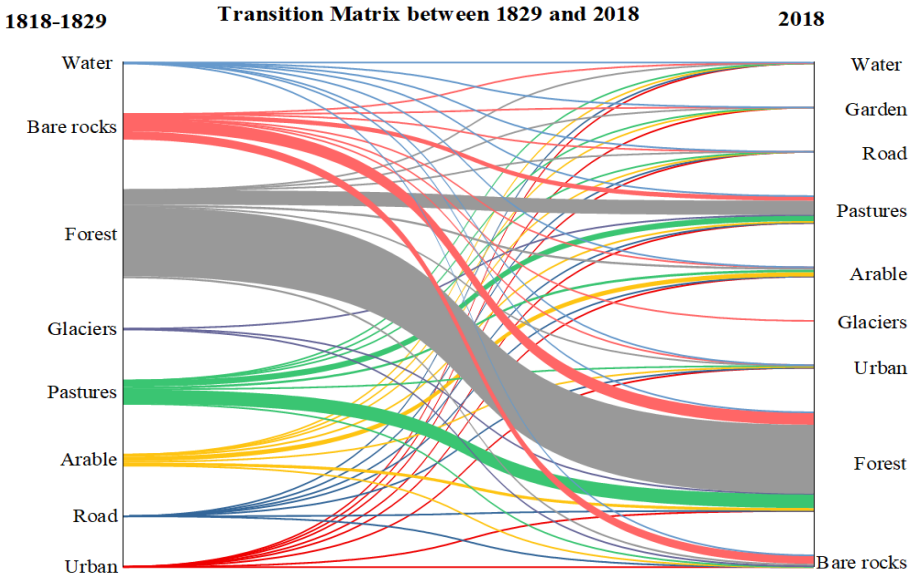

Figure 7. Schematic diagram of LULC transition matrix over the entire study period (1829-2018), corresponding to Table 7.

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Discussion

The LULC Change Drivers in the Piave River Basin

This study documented the main LULC transitions and their corresponding drivers, including demographic, agricultural and environmental policies, socio-economic, and climatic influences that reshaped the Piave River Basin and the Eastern Italian Alpine regions since the early first half of the 19th century, albeit attributing and separating these forces is intrinsically complex due to their interrelations and functioning on different temporal and spatial scales. However, based on several available studies and existing evidence, the dominant drivers can be identified.

Studies conducted by Paul and Bolch (2018) and Nigrelli et al. (2015) revealed that both global and Alpine glaciers are currently retreating, and barren surfaces are becoming available for plant and other biological colonization due to the continued period of climatic warming since the end of the Little Ice Age. Reinthaler and Paul (2025) also indicated that the formerly glacierized catchments in the Alps, particularly the Italian Dolomites, have been ice-free since 2000 due to temperature increase. The above report supported this study findings, suggesting that climate warming played an important role in the reduction of bare rocks and glaciers and the progressive expansion of forest class in the Piave basin over the entire study period.

The reduction of arable land and the subsequent pastures and forest class successions in the Piave Basin, initiated in the early 19th century and later pronounced following the First World War, was driven by agricultural land abandonment and rural depopulation (Anselmetto et al., 2024; Cocca et al., 2012; MacDonald et al., 2000). The traditional agropastoral practices, including managed alpine grazing, rotational meadow and terrace cultivation systems, substantially declined due to accelerated urban migration, rising labour costs, and economic shifts from mountain agriculture to more productive lowland farming and highly competitive industrial employment, resulting in a consequent vegetative expansion on these abandoned pastures and farmland, yielding an increase in forest coverages as clearly recorded in this study. The result also agrees with Munteanu et al. (2014), who conducted a meta-analysis of agricultural and forest land change in the Carpathian region. They found that agricultural land use increased in the Austro-Hungarian Empire but sharply dropped thereafter.

Additionally, the piedmont zones and valley-floor primary agricultural lands were colonized by peri-urban and urban expansion (Ferrario, 2010; Vallerani, 2012). The ‘Third Italy’ model commissioned post-World War II boomed the economy in the Veneto region by developing small- and medium-sized enterprises and demanding land for industrial, commercial, and residential uses, resulting in lowland agricultural losses in the basin (Bartolini, 2021). Both these dynamics, agricultural lowland intensification and upland abandonment, characterize the mountain landscapes across Europe (Dax et al., 2021; Eriksson et al., 2002; Munteanu et al., 2014).

In recent periods (1990-2018), the European Union's rural development and agricultural policy also played an essential role in modifying the LULC dynamics. Agri-environment support schemes, reforestation/afforestation incentive programs, and rural development projects under successive changes have simultaneously inspired landowners to manage traditional pastures, thereby enabling the grassland/pasture recovery observed after 1990, while offering incentives for marginal land reforestation/afforestation (Ackrill, 2000; Keenleyside et al., 2010; Nazzaro & Marotta, 2016; Primdahl et al., 2003).

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LULC Trend Comparison with the Alpine Regions

The long-term LULC trajectories documented in this study are most probably consistent with other overall patterns reported in the Carpathian Catchments and Alpine Basins in Switzerland, Austria, and Italy. The forest cover expansion was recorded across the mountains of the Carpathians ((Munteanu et al., 2014), the Swiss Alpine region (Gellrich & Zimmermann, 2007), and the Italian Apennines (Garbarino et al., 2020; Malandra et al., 2018), the Austrian Alps (Tasser et al., 2007), and the South Carpathian River; Pesceana River basin between 1990 and 2018 (Măceșeanu et al., 2026). In all these and others, the fundamental driver is agricultural land abandonment linked with rural depopulation; climate warming is identified as an additional facilitator.

The substantial decline of the Bare Rocks/Sands cover class recorded in this study is higher relative to other reports from Alpine regions. This likely indicates the particularly large proportions of rocky terrain in the Piave River basin and the dramatic post-Little Ice Age reductions of these classes. The highly significant loss of glacier cover also reflects an irreversible disappearance in the basin and agrees with the glacial retreat recorded in the Alpine region, where many comparable glacier patches disappeared (Securo et al., 2025; Sommer et al., 2020).

The Urban and Built-Up Area sprawl trend viewed in the Piave drainage basin is almost consistent with the broader urbanization extents reported across subalpine and Alpine catchments (Ferrario, 2010; Romano & Zullo, 2016; Vallerani, 2012), where the expansion of settlements was increasingly concentrated along transport corridors and valley floors (Perlik et al., 2001). As discussed by Measure (2020), tourism, economic, and population growth drove similar trends of urbanization in the European Alpine regions, converting the natural and agricultural lands into built-up areas.

LULC Evolution Implications for Natural and Cultural Heritage, Hydrology, and Ecology

Natural and Cultural Heritage Implications

The historical electronic cartographical data, particularly the Habsburg Military Survey, used for this study and others, by themselves, are invaluable digital artefacts, reflecting the natural and built land use features, exceptional records of the Alpine landscape and Central Europe during the pre-industrial period, as well as before and after the end of the Little Ice Age, providing excellent possibilities for long-term landscape change detection assessment (Timár et al., 2010).

Their thorough, systematic georeferencing, digitization, vectorization, and synchronization with modern reference maps, as presented in this work, enhance the digital cartographical valorization and preservation, enabling the land feature-historical content and extent of these maps to be easily accessible and available to diverse users, including landscape architects, environmental and water resource planners, hydrologists, historians, and geographers.

The LULC changes reported in this manuscript offer insight into tangible cultural and natural heritage feature transformations embedded in the landscape of the Piave Basin. The traditional mountainous agropastoral economic practices, together with their infrastructure, such as managed terrace walls, pastoral huts or shepherd shelters, farm hamlets and timber houses were visible in the digital cartography and maintained during the Habsburg period but are now lost in the modern landscape, as these agropastoral economies became abandoned. The small Dolomite glaciers and year-round permanent snow cover disappeared; the original forests were replaced with managed ones; the Piave's braided river was reshaped, causing riverine habitats to vanish; military roads were ruined and abandoned; and the pre-World War I villages were destroyed. These former heritage features were obscured from their original view and physically degraded by managed landscape reforestations through frost-thaw and root penetration processes.

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The Habsburg-era path and road networks documented in this study may inform contemporary environmental management in mountainous and rural areas by identifying ancient routes that can be rehabilitated for viable, sustainable ecological and tourism connectivity. Containing a wide range of heritage sites, including a UNESCO World Heritage site, the Piave Basin presents a substantial opportunity for natural and cultural heritage integrated landscape management that utilizes historical map data to base modern planning decisions on an understanding of the dynamics of long-term landscape change.

Hydrological Implications

The LULC evolutions recorded in this work have significant implications for the water balance components of the Piave Basin. The large-scale decline in glacier coverage (37.03 km^2) reflects a progressive reduction in glacial meltwater contributions to summer runoff, impacting the seasonal Piave River discharge regime. Glacial meltwater contributions are most probably essential during the summer season (June-September), when precipitation becomes relatively low, and their reduction may increase the severity and frequency of summer low stream flows, with effects for in-stream and river ecological functioning, water power generation, and water supply (Huss & Hock, 2018).
The substantial increase in forest cover (297.57 km^2) from the Habsburg era to the present day is expected to significantly alter the basin's hydrological water balance, typically by increasing evapotranspiration. Compared to arable land and grasslands, forest cover generally exhibits high rates of evapotranspiration, particularly during summer. This indicates that, relative to the open landscapes of the Habsburg era, forest cover leads to reduced annual runoff and the attenuation of peak flood levels (M. Balistrocchi et al., 2021; Ranzi et al., 2016).
The dramatic reductions of Bare Rocks/Sands, particularly those of the declining active gravel deposits and braided stream and river channels along the valley bottoms, have significant implications for sediment transport and flood dynamics. In its lower and middle reaches, the historic Piave River was described as having an extensive braided pattern and planform, as well as wide gravel-deposited riverbeds, a condition observed in the Habsburg digitized maps of Bare Rocks/Sands LULC class and in an abundant water course along the valley floors.
The progressive active channel reshaping and narrowing, and former gravel and sand colonization by riparian vegetation and eventually pasture and agricultural land have significantly declined the capacity of fluvial systems to route and store flood discharges, leading to an increase in the lower valley hydraulic risk (N. Surian, 1999; Nicola Surian, 1999; Surian et al., 2009).

Biodiversity and Ecological Implications

The landscape transitions analyzed in this study may have potentially contrasting and complex implications for ecosystem and biodiversity services in the Piave River basin. The large-scale forest expansions can be appropriate for woodland habitats and benefit various forest-dependent species, including large mammals (roe deer), raptors, and multiple woodland passerines, while they threaten open habitats and specialized grassland species that are dependent on traditional agropastoral environments, including many invertebrates and some vertebrates (ground-nesting birds), and many plants, as characterized in Alpine pastures and meadows (Laiolo et al., 2004; Rolando et al., 2007; Sirami et al., 2007).
The irreversible loss of glacial habitats in the Piave Basin reflects the functionally unique cryophilic community extinctions, including psychrophilic algae, ice worms, macroinvertebrates and insect communities that are dependent on the streams of glacial meltwater (Jacobsen et al., 2012)

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Conclusions

A systematic, comprehensive and quantitative analysis of long-term landscape change evolution in the Piave Basin is reported, covering two full centuries, from the Habsburg-Second Military to the present CORINE-2018 LULC dataset. Through systematic re-georeferencing, manual vectorization of ancient digital cartographic maps, and comparison with current high-resolution satellite-based classifications, the study shows a modified landscape driven by combined influences, including rural depopulation and urbanization, agropastoral land abandonment, environmental and agricultural policies, and sustained climatic warming following the end of the Little Ice Age.

Re-georeferencing the pre-existing georeferenced Habsburg Second Military survey at the basin scale enhanced the spatial accuracy and alignment with the actual base maps, supporting the reliability of the documented LULC transformations.

The most prominent transformations were observed in Glaciers (-98.67%) and Bare Rocks/Sands (-53.27%), attributable to prolonged climate warming since the Little Ice Age recessions. These formerly glaciated and bare rock surfaces were gradually colonized by vegetation, resulting in a notable forest cover expansion (+12.27%) and a more recent increase in pastures/grasslands (+14.5%), which also reflects the EU agricultural and environmental policies implemented after 1990 and spontaneous succession. At the same time, arable land was reduced by 13.79% due to the abandonment of marginal mountainous and rural agricultural practices, while urban/built-up areas expanded significantly (+667.85%) in transport corridors and valley bottoms, as a result of socio-economic growth and demographic shifts.

These transformations closely resemble patterns reported elsewhere in the Carpathians and Alps, reinforcing climate warming and agropastoral mountain land abandonment as contemporary landscape change's dominant drivers, in addition to basin-scale pressures; more importantly, the scale of glacier and barrens, connected to the highly glaciated headwaters and high terrain of the Piave Basin. Furthermore, the study assessed the significant implications of landscape transformations on tangible natural and cultural heritage, hydrological regimes, and ecosystems and biodiversity.

More importantly, this study illustrates the significance of using the underutilized historical digital cartography, particularly the Habsburg Second and Third Military Surveys, as a rigorous and invaluable source of data for detecting landscape change predating the satellite era.

Future research can extend and adapt this approach to other such data-rich Alpine regions to reconstruct a more comprehensive basin-scale baseline and may also assess these LULC transformations in coupling with climate change to better estimate their impact on the evolution of the hydrological water cycle, water resources, environmental management, flood risk, and monitoring of ecosystem and biodiversity.

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